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PLASMA CATHODE FOR E-BEAM LASERS

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The objective of this program is to develop the plasma cathode electron gun and to demonstrate that it has properties which make it suitable for application to E-beam lasers. The source of electrons in this new and advanced electron device is a plasma generated within a low-voltage hollow-cathode discharge; a thermionic emitter is not required. Electrons extracted from the plasma pass through a triode-type control grid structure and are accelerated to high energies in a

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Many of the basic characteristics of the plasma cathode E-gun concept have been previously demonstrated with devices producing beams of up to 150 cm^2 in area at beam energies of 150 kV, and at pulsed current densities of 60 mA/cm^2. At lower voltages, pulsed and cw current densities of up to 1 A/cm^2 and to 1 mA/cm^2 respectively, have been obtained. The current density has been found to be uniform to within typically ±5 to 10%, and it has been verified that the beam is monoenergetic. Furthermore, scaling has been demonstrated in a 200-cm long cylindrical discharge device, and a compact high-voltage feedthrough design has been perfected which is applicable to large scale devices.

Recent work has been directed toward construction and evaluation of a 4 x 40 cm and a 5 x 125 cm plasma cathode E-gun, each with a compact design ideally suited to incorporation into a laser system. The 4 x 40-cm E-gun has been operated under primarily cw conditions at a beam energy of 160 keV and an average current density of 0.2 mA/cm^2 (power supply limit) for 5 s in tests performed with a solid collector in place of the foil window (this was done in order to avoid the complexities of window cooling). Tests have also been performed to determine the parametric characteristics, high voltage stand-off capability, current density distribution, sensitivity to magnetic fields and contamination, and stability. These tests have verified the basic efficacy of the plasma cathode E-gun concept.

Data from the 4 x 40-cm device has been incorporated into the design of the recently completed 5 x 125-cm E-gun. This device, which is intended for cw operation with a laser, will produce a focused beam ($\sim 10^{\circ}$ half-angle) in order to counteract the effects of scattering by the foil window at the beam edges. Testing of this device is presently in progress.

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I. INTRODUCTION

The objective of the plasma cathode program is to develop a new type of electron gun suitable for electron beam plasma conditioning of large volume electric discharge lasers.[1] This gun employs a plasma, which is generated within a low-voltage hollow cathode discharge, as the source of electrons rather than a thermionic cathode as in conventional electron guns. A pulsed or cw electron beam is extracted from the plasma and is controlled either by varying the discharge current or by means of a grid system in a manner very similar to that employed in standard vacuum triodes. This permits the generation of any desired beam pulse shape. After extraction from the discharge plasma, the electron beam is accelerated to energies in the range of 100 to 200 keV prior to passing through a thin metal foil window and into the active laser region.

The plasma cathode electron gun is characterized by its simplicity, and has advantages over conventional thermionic devices which include:

- Simple, rugged construction — No inherently delicate heater elements are required, and since operation is obtained at near ambient temperatures, thermal stress problems are minimized.

- Insensitivity to contamination — Since high temperature, low work function surfaces are not required, cathode poisoning is not possible; if the foil window ruptures, the plasma cathode will not be damaged.

- Suitability for large area beam production — scaling to any desired size is achieved by simply enlarging the device dimensions without the constraints imposed by heater element design.

- Instantaneous startup — No warm-up time is required since beam extraction can be obtained immediately after discharge ignition which occurs in about a microsecond.

- Low power consumption — The plasma cathode consumes less power from power supplies floating at high voltage than do equivalent thermionic devices.

- Minimal pumping requirements — Because the plasma cathode E-gun operates at a helium pressure of about 30 mTorr, it is inherently insensitive to pressure changes resulting from outgassing. Furthermore, sputtering occurring in the cold cathode discharge serves to pump the chemically active outgassing products thereby, in fact, permitting sealed-off operation.

- Low cost — The inherent structural simplicity of the plasma cathode and low parts count is indicative of substantial cost savings in relation to thermionic devices.

Several E-guns of other types are described in previous literature, some of which have been used on lasers. These employ either a high-voltage glow discharge or a low-pressure incipient vacuum arc. The plasma cathode gun is unlike either of these types and is expected to have advantages which include:

- Good foil penetration for plasma conditioning — Efficient foil penetration is achieved due to the highly monoenergetic property of the beam generated by the plasma cathode gun. Other gas discharge devices, in which a plasma sheath exists in the region between the accelerating electrodes, produce a broader energy distribution with substantial amounts of electrons at lower energy; this results in reduced foil penetration ability.

- Long pulse and cw capability — High-voltage glow discharge devices are only capable of pulsed operation at pulse lengths which are dependent on the beam voltage and current. The incipient vacuum-arc devices are inherently limited to short pulse ($\lesssim 5\ \mu s$) operation. The plasma cathode can operate in either pulsed or cw modes.

- Long life — Since the plasma cathode incorporates a relatively low voltage (500 to 800 V) discharge, sputtering is greatly reduced in comparison to high voltage glow discharge devices in which ions with energies comparable to the E-beam energy strike the cathode.

- Improved control — The triode type grid control utilized with the plasma cathode gun is expected to be simpler and more versatile than that of diode type hign voltage discharge devices. The high acceleration voltage can be continuously applied in the present device and rectangular-pulsed beam operation is achieved by pulsing the hollow cathode discharge or the control grid. Operation with other pulse shapes can be obtained by proper temporal biasing of the control grid.

- Higher power efficiency — Since electrons are produced in a low voltage gas discharge, the power efficiency of the plasma cathode is much higher than other plasma guns where ions reach the cathode at high energies.

- Reduced power supply complexity — Pulsed operation of the plasma cathode is achieved simply by pulsing the low-voltage hollow cathode discharge. Other plasma guns require that the high voltage be pulsed, which is difficult to do efficiently and at high repetition rates.

Up to the beginning of the subject reporting period, investigation and demonstration of the plasma cathode concept has been undertaken with a series of test devices, none of which have designs which are readily suitable for incorporation into laser systems.[1] The purpose of this contract, over the past six months, has been to combine the previous individually tested E-gun components into two practical devices. The first, a high-voltage 4 x 40-cm E-gun, was designed and fabricated under company funding, and assembled and tested under the present contract. Although capable of both pulsed and cw operation, the evaluation program has been directed primarily toward achieving reliable cw operation.

Data, which has been acquired through evaluation of a number of modifications to the initial 4 x 40-cm E-gun design, has been incorporated into the design of the recently completed 5 x 125 cm device. This gun is designed primarily for cw operation, although minor modifications will permit efficient operation in a high current pulsed mode. The grid structure of this device is curved in order to provide a slightly convergent ($\sim 10^{\circ}$ half-angle) beam in order to compensate for scattering by the foil window. Testing of this device is presently underway.

In the following section the technical approach of the program will be discussed and both of the plasma cathode E-guns will be described in detail.

II. TECHNICAL APPROACH

This section describes the basic concept of the plasma cathode electron gun and outlines the experimental program performed up to the beginning of the subject reporting period.

A. Basic Concept

A schematic diagram of the plasma cathode electron gun is shown in Fig. 1. The device consists of three major regions: (1) the plasma generation region in which the beam electrons originate, (2) the extraction and control region where electrons are extracted from the plasma and transported in a controlled manner into the acceleration region, and (3) the high-voltage acceleration region where the electrons are accelerated to high energies prior to passing through a thin metal foil window and into the laser medium. These regions are comparable to the thermionic cathode, control grid, and the grid-to-anode space of a conventional triode.

The plasma generation region in the present device consists of a low-pressure glow discharge struck between the cold, hollow cathode surfaces and the anode grid, G1. This type of discharge has been chosen because of its stability, reliability, simplicity, and ability to operate at the low gas pressures required to preclude gas breakdown in the acceleration region. In the present application, the discharge operates at a voltage, which is approximately independent of current, of typically 500 to 800 V with helium at pressures typically in the range of 20 to 50 mTorr. Helium is used because He^+ ions have relatively low sputtering yields and because it has high-voltage breakdown characteristics which are superior to those of other gases.

The major characteristic of the hollow cathode discharge is that most of the plasma volume is surrounded by the cathode surface. The discharge, which is sustained by secondary electron emission due to ion bombardment of the cathode surface, is operated in a regime where the rate of ion generation by ionization in the discharge volume is sufficient to maintain the plasma potential slightly above anode

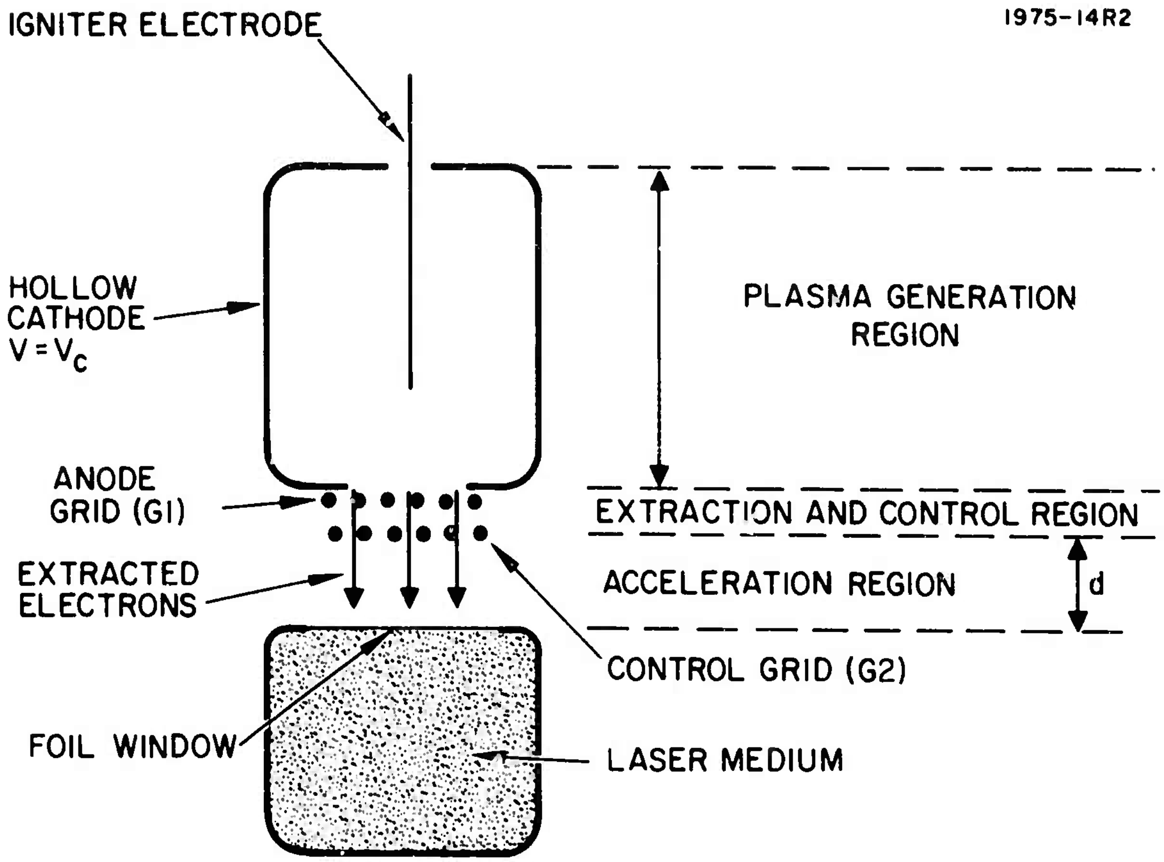

Fig. 1. Schematic of the plasma cathode electron gun.

potential. Because of the large cathode-to-anode area ratio, most ions leaving the discharge are accelerated through the cathode sheath, and utilized with maximum efficiency for secondary electron production, thus minimizing the rate of ion generation required per emitted electron. Furthermore, the secondary electrons accelerated back through the cathode sheath are repeatedly reflected from opposing cathode surfaces. This results in a high probability for making ionizing collisions at low gas pressures where the electron ionization mean-free path exceeds the dimensions of the discharge. At sufficiently low pressure, however, the ionization probability drops to a level for which the discharge cannot be maintained. This determines the minimum working pressure.

Electrons are extracted from the discharge plasma through the anode grid, G1, and pass through the control grid, G2, into the acceleration region. Voltages of typically 0 to -100 V relative to G1 are applied to G2 in order to control the beam intensity from maximum to near cutoff. Grid G2 also serves to provide isolation between the low-voltage discharge region and the high-voltage acceleration region. Alternately, control of the beam current is possible through variation of the hollow cathode discharge current through the potential of G1.

Width d of the acceleration region is critical to the successful operation of the plasma cathode electron gun, since the entire electron acceleration voltage is applied across this gas-filled gap. In order to avoid breakdown in this region, width d must be maintained at a value larger than that which would result in vacuum breakdown, and smaller than the value which would result in Paschen breakdown. Figure 2 illustrates this situation for a gas pressure of 50 mTorr. Both breakdown curves represent conservative values based on data generated in our experiments and quoted in previous literature.

As seen from Fig. 2, there is a region between the two breakdown characteristics where high-voltage operation is possible without incurring breakdown. In the present work, d is chosen for a given maximum operating voltage (150 to 200 kV) to have the operating point

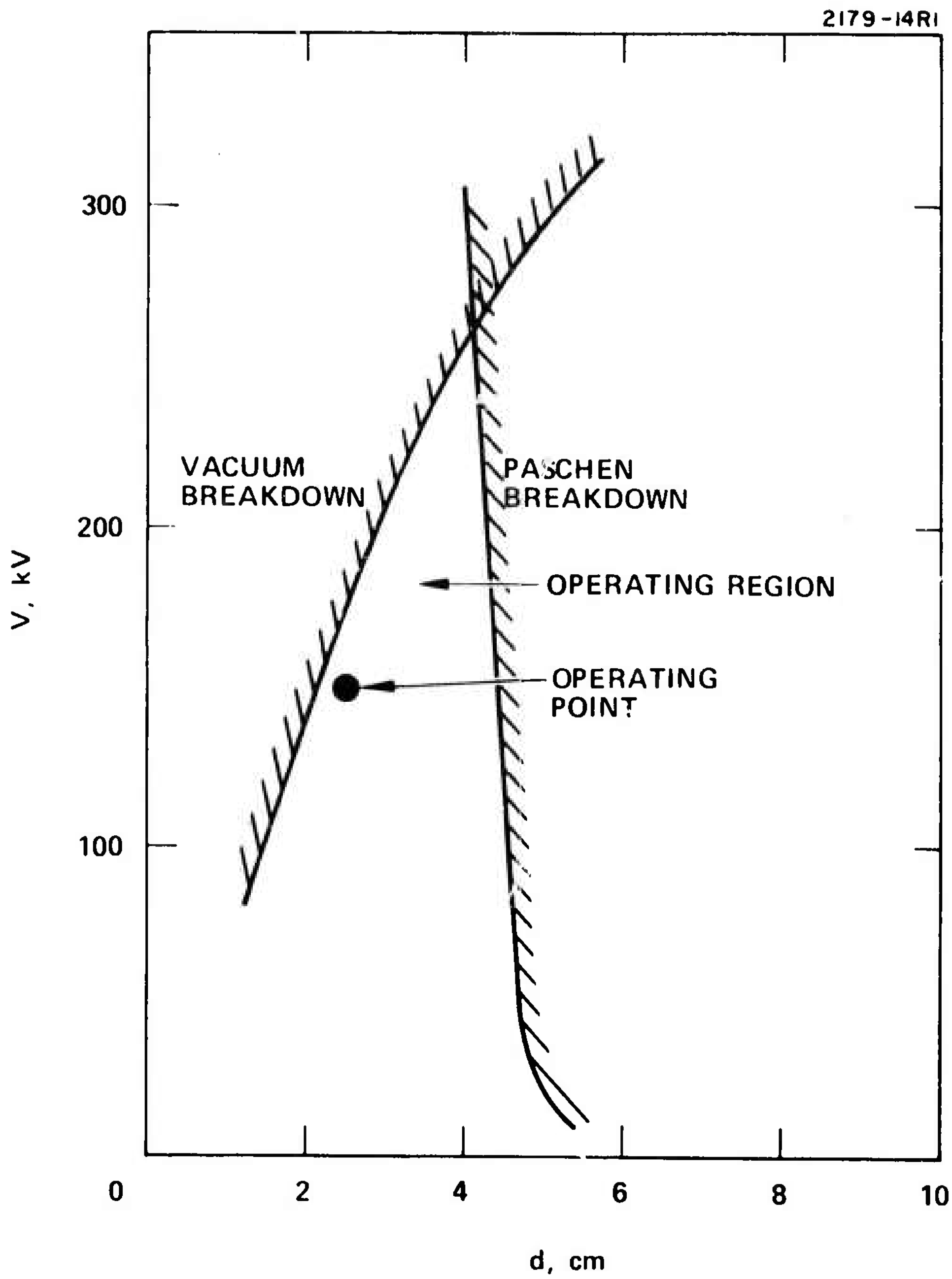

Fig. 2. Low pressure breakdown voltage in the plasma cathode accelerating region as a function of the gap width, d. The Paschen curve is for a pressure of 50 mTorr.

nearer to vacuum breakdown characteristic than the Paschen breakdown curve. This is desirable since this characteristic is expected to be more stable in time than the Paschen curve which is sensitive to the presence of outgassing products. As can be seen from the figure, this design is conservative and accelerating voltages of up to 250 kV may be possible with a helium pressure of 50 mTorr; even higher voltages may be possible at lower pressures.

Figure 3 summarizes the voltage and current requirements for the plasma cathode E-gun which are based on data obtained under typical pulsed and cw operating conditions. The current level of 2 I_B supplied by the high-voltage source assumes a transmission of 50% for the foil window assembly. Measurements on existing plasma cathode devices indicate that the discharge anode current is about equal to the beam current incident on the foil window structure. Therefore, the discharge power supply also operates at 2 I_B in either pulsed or cw mode, depending on the desired application. As is shown, the control grid operates at a slightly negative potential relative to the anode and collects a current of ~15% of the extracted current. The igniter, which provides the background ionization to permit initiation of the hollow cathode discharge without requiring excessive voltages, operates cw at typically 10 mA and 300 V.

B. Previous Development

The basic ingredients of the plasma cathode E-gun development program prior to the subject reporting period are outlined below.[1]

1. Discharge Configuration – The hollow cathode discharge was chosen from several candidates as the simplest way to produce a stable discharge at low pressures. The thin wire igniter was adopted as the means for initiating the hollow-cathode discharge without the need for high voltages. An electrode configuration permitting beam extraction and controlled entrance into the acceleration region was developed.

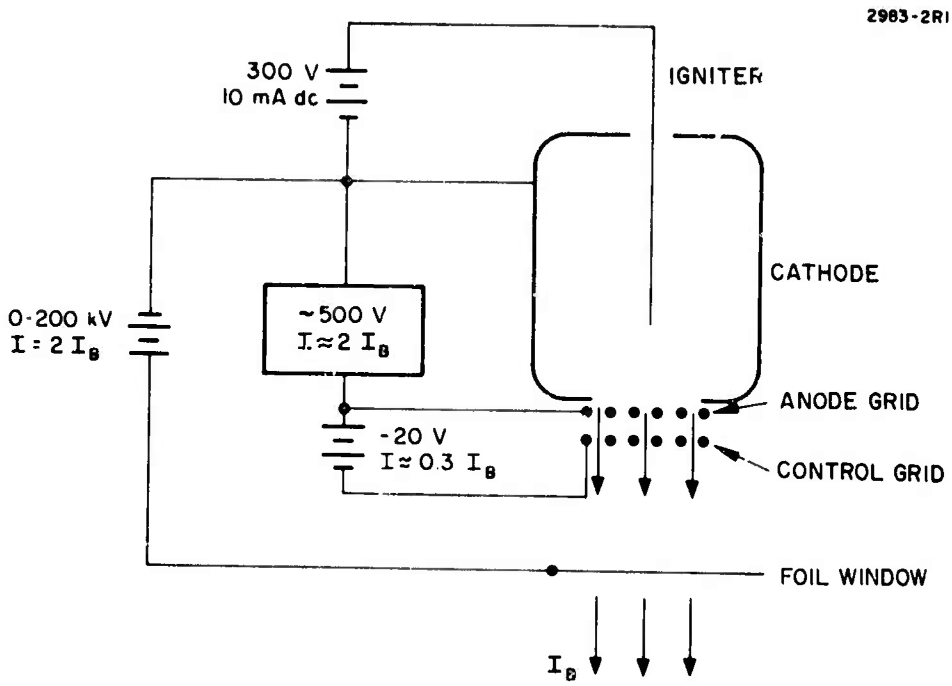

Fig. 3. Plasma cathode power supply schematic.

2. Beam Acceleration Region – Measurements of the Paschen breakdown characteristics were obtained with and without the presence of an electron beam produced by a small thermionic E-gun. It was found, as expected, that the pressure at which breakdown occurred was reduced by less than 20% at 100 kV with the beam on. A value of Pd = 0.20 Torr-cm was established for design purposes.

3. Beam Generation – Electron beams 150 cm^2 in area were produced at energies of 150 keV and current densities of 60 mA/cm^2 in 100 μsec pulsed operation. In other tests at lower voltages, pulsed and cw current densities of up to 1 A/cm^2 and 1 mA/cm^2, respectively, were measured. All of these data were obtained with a solid collector plate in place of the foil window.

4. Current Density Distribution – Measurements obtained with a 10 x 15 cm plasma cathode E-gun demonstrated current density distributions uniform to ±5%. Similar measurements, under both pulsed and cw operating conditions, with a low-voltage 4 x 40 cm device indicated uniformities of ±5% and ±10% in the long and short dimensions, respectively. Various designs for field shaping electrodes and discharge partitions to influence the distribution were evaluated.

5. Electron Energy Distribution – A retarding Faraday probe was used to measure the electron energy distribution of a small portion of the beam. The energy spread was measured to be monoenergetic to within ±1.4%. The actual energy spread is expected to be less than these measurements indicate on the basis of instrumentation effects. In addition, transmission measurements through a 0.00125-cm thick titanium foil, in combination with calculated transmissions as a function of electron energy, verify that the beam is monoenergetic.

6. Development of Scalable Designs – A coaxial E-gun configuration was developed which readily permits scaling to large dimensions. A 15-cm diameter, 200-cm long cylindrical hollow-cathode discharge with four electrically isolated anode sections was operated. These tests indicate that good (better than ±5%) macroscopic uniformity is achievable provided the anode sections are separately ballasted

with resistors of equal value which consume less than 10% of the total low-voltage discharge power. Finally, a compact high-voltage feedthrough, which operates under the simultaneous constraints of vacuum, Paschen, and dielectric bulk and surface breakdown, was developed and successfully tested at up to 200 kV.

The previous developments outlined above have provided all the documentation and design ingredients required to build the large scale plasma cathode electron guns which are described in the next two sections.

III. THE HIGH-VOLTAGE 4 x 40 cm PLASMA CATHODE ELECTRON GUN

The objective of this portion of the plasma cathode development program is to provide an intermediate sized, practical E-gun suitable for evaluations which are relevant to large scale devices. In particular, the experimental program which began following completion of the device at the end of January, has been specifically directed toward supplying cw design data applicable to the 5 x 125 cm E-gun concurrently under development. The 4 x 40 cm gun was initially designed and fabricated under company funding with existing component parts as the foundation. Assembly, testing, and design modifications have been performed under the present contract. Although this device is being presently employed as a test vehicle it is designed so as to be fully adaptable to an E-beam laser.

A. 4 x 40 cm E-Gun Design

The design of the high-voltage 4 x 40 cm plasma cathode E-gun is based directly on that of two proven components, the low-voltage 4 x 40 cm device and the compact high-voltage feedthrough, which have been described in the previous semiannual report.[1] Figure 4 shows a schematic cross section of the basic coaxial design and Fig. 5 illustrates the layout of the E-gun. Figure 6 provides a photograph of the two major E-gun components, the inner cylinder which contains the hollow-cathode discharge, and the outer grounded cylinder, which contains the thin foil window and serves as the vacuum envelope.

The hollow-cathode discharge chamber is formed by the 12-cm i.d. inner stainless steel cylinder. Use of a cylindrical configuration, previously evaluated with the low-voltage 4 x 40 cm device, is based on the ease of construction and suitability for extension to larger scale devices. Previous tests have demonstrated that a highly uinform discharge can be established in this configuration.

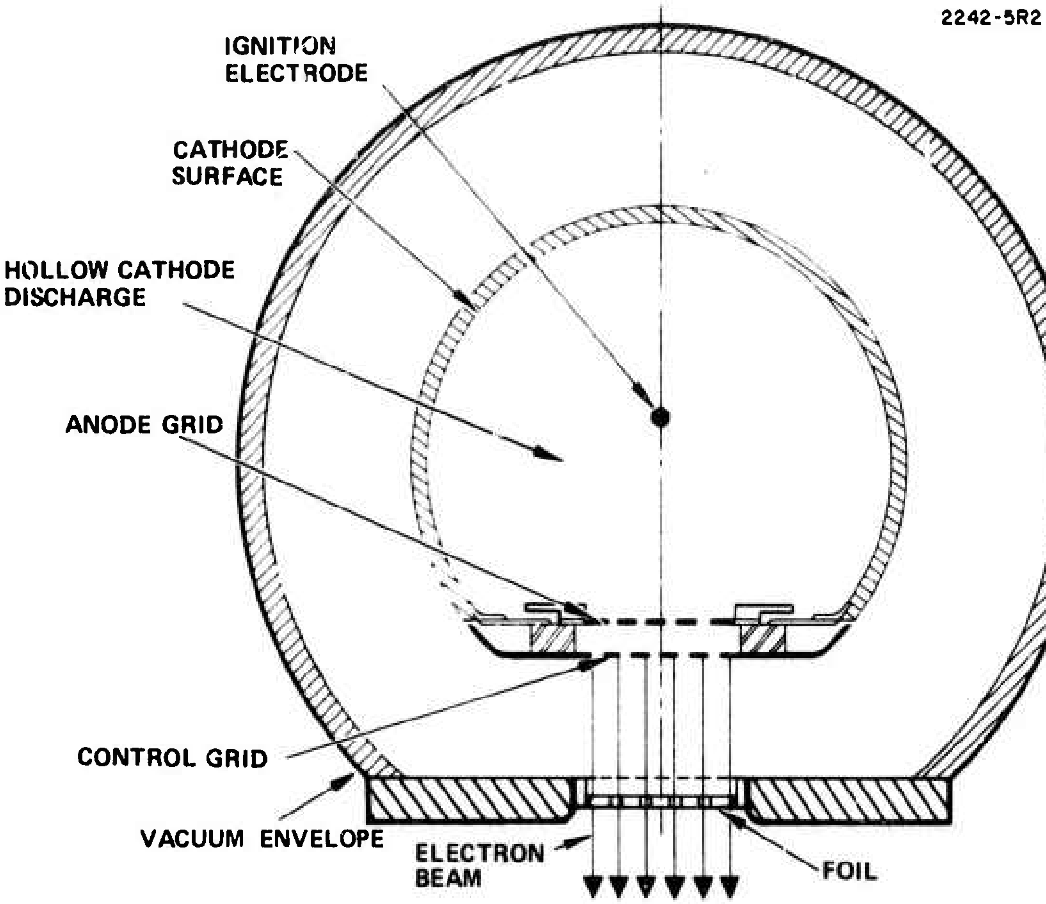

Fig. 4. Cross section of the coaxial E-gun design.

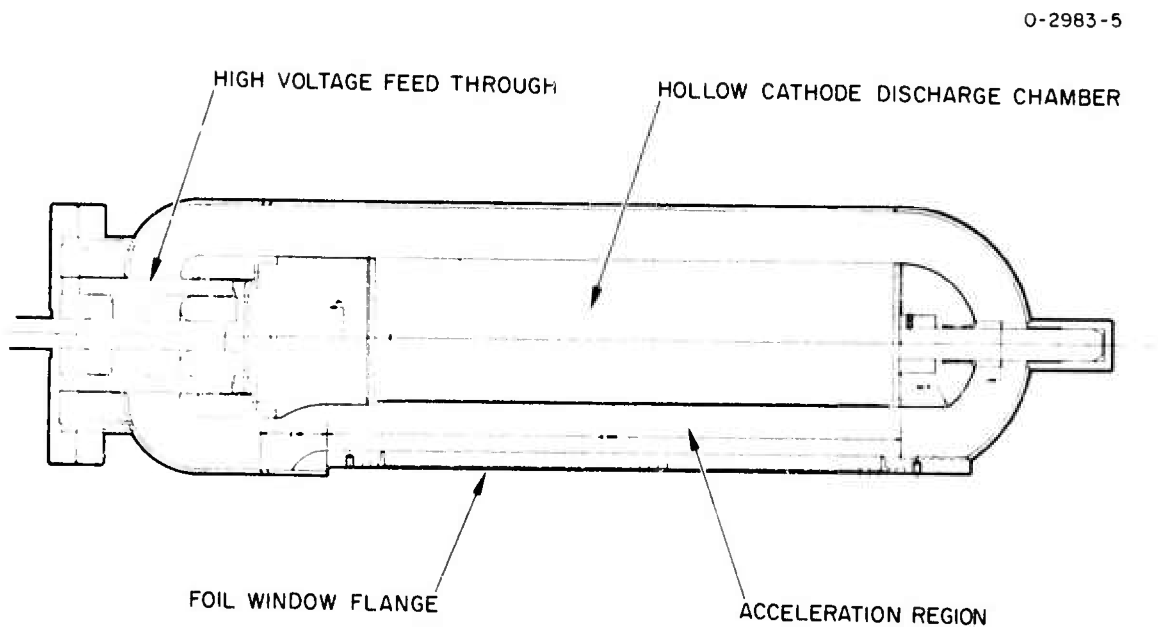

Fig. 5. High energy 4 x 40 cm E-gun.

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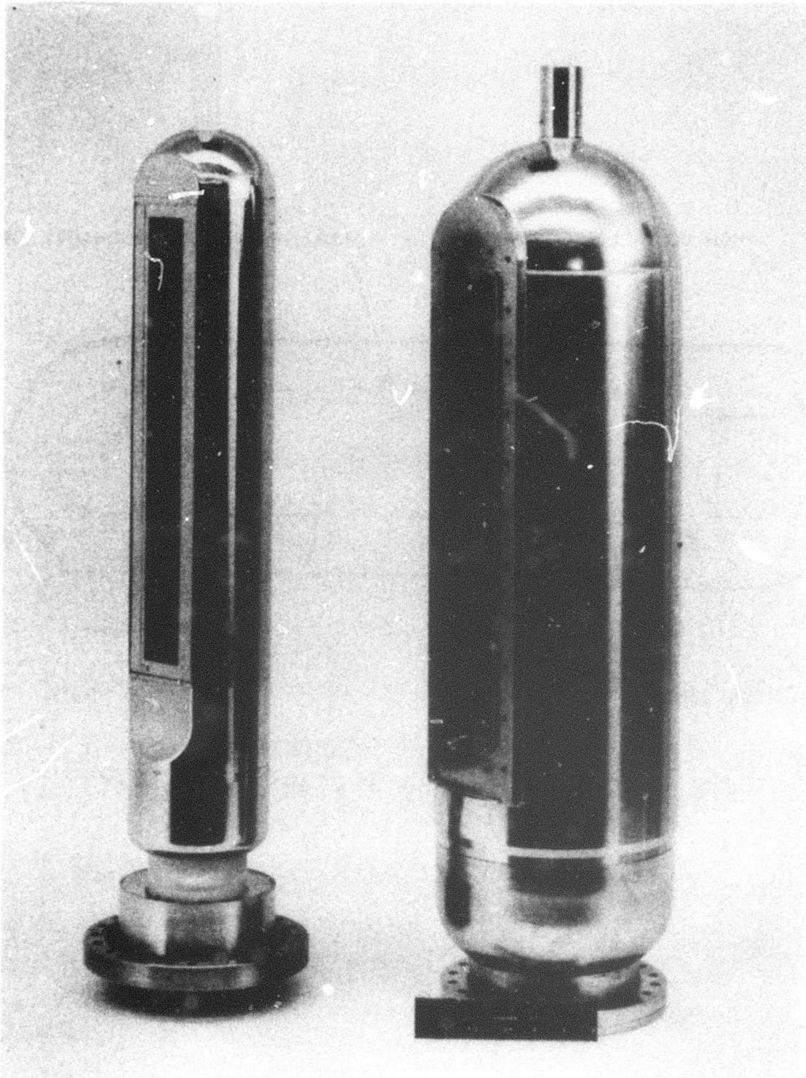

Fig. 6. Inner and outer cylinders of high-voltage 4 x 40 cm E-gun.

The hollow-cathode discharge runs at a voltage, typically 500 V, which is largely insensitive to the discharge current. The differential resistance of the discharge is always positive, thereby obviating the need for a large ballast resistance to provide good stability. The operating voltage depends on the helium gas pressure and the presence of contaminants. The anode grid is formed from square, 52% transparent stainless steel mesh having a 0.014-cm wire diameter. This mesh is mounted on a stainless steel frame which serves as a sputter shield for the ceramic pieces which support it. The dependence of the ratio of extracted beam current-to-anode current on anode grid transparency has not been investigated. It is expected, however, that this ratio is roughly proportional to the transparency.

The control grid serves to provide electronic beam control and to insure isolation between the hollow-cathode discharge and the acceleration region. In the present experiments a square stainless steel mesh with the same geometry as that of the anode grid is used. It is spaced 0.8 cm from the anode grid, a distance which is mechanically convenient and which should not be critical. The equivalent triode amplification factor of this grid for the present geometry is about 4×10^3 (Ref. 2) so that the potential just upstream of the control grid, due to the beam acceleration potential, is on the order of 50 V. As will be seen later, in the discussion of experimental results, the hollow cathode discharge supplies an emission limited beam. Control is achieved by reverse biasing the control grid so as to retard electron motion through it. Since the discharge plasma potential is close to that of the anode, and because the plasma electron temperature is low (~3 eV), substantial beam current modulation is obtained for grid voltages on the order of 50 V negative with respect to the anode grid. Under these conditions the interception by the control grid is typically less than 10% of the extracted beam current, much less than would be expected on the basis of the grid transparency. This results from the penetration of the accelerating potential through the grid which tends to focus the low energy incident electrons through the grid apertures.

The inner and outer cylinders (refer to Figs. 4 and 5) are contoured so that a spacing of approximately 4 cm is maintained at all points between the two cylinders. This spacing is chosen assuming a 200 kV operating voltage. With reference to Fig. 2, a smaller gap would result in excessive field strengths which could cause vacuum breakdown. A larger gap would reduce the gas pressure range for which operation would be possible. Maintenance of this spacing is accomplished by the use of field shaping electrodes. Electrodes are provided which extend the plane of the control grid, G2, smoothly into the cylindrical cathode surface. Contoured electrodes are also provided at each end of both the inner and outer cylinders in which to minimize electric field concentrations. All parts of both cylinders are formed from nonmagnetic 304 stainless steel which is electropolished in order to minimize sharp surface protrusions.

The surface of the cylindrical vacuum envelope is mated with the flat window support flange as shown in Figs. 4, 5 and 6. A wire mesh "high-voltage anode" is provided between the thin foil window and the acceleration region in order to maintain the 4-cm acceleration region width and to avoid focusing of the electron beam. This wire mesh greatly reduces the potential gradient in the region between it and the foil window and thereby reduces the contribution of ions produced in this region, as well as electrons reflected from the foil, to gas breakdown processes. Such a potential defining plane will always be necessary since it is desirable to: (1) locate the foil window close to the laser medium, and (2) provide substantial flange thickness so that it will not distort due to the pressure difference across the vacuum chamber wall.

For high average beam current guns the design of this high-voltage anode grid is strongly influenced by its (1) thermal properties, (2) electrostatic focusing, (3) electrostatic field enhancement, (4) effect on Paschen Breakdown, and (5) beam interception. (This will be discussed in detail for the 5 x 125-cm E-gun.) In the present design a 78% transparent square molybdenum mesh formed from 0.0125-cm diameter wires has been used. Radiation cooling of this mesh permits it to withstand high input power densities without melting.

Electrical power is supplied to the cathode, anode grid, control grid, and igniter electrode through the high-voltage feedthrough (refer to Fig. 5). This component must operate under the constraints of Paschen breakdown in addition to those associated with the other forms of electrical breakdown usually encountered in vacuum high-voltage feedthroughs.

A coaxial cable 2.3-cm diam passes through the center of the assembly to a four-pin connector located within the innermost field shaping electrode. The center conductor of this cable is a copper tube which facilitates routing of four conductors to the connector. The copper tube carries current to the cylindrical discharge cathode. The field shaping electrodes within the ceramic tube are designed so that the electric field lines merge smoothly from the 4-cm gap into the coaxial cable.

A solid AL-300 alumina post is used to provide mechanical support of one end of the inner cylinder.

B. Experimental Arrangement

The experimental layout is depicted in Fig. 7. The E-gun is located within a lead lined box in order to protect personnel from x-rays. Low voltage power is supplied from a floating deck and isolation transformer. The tube can be evacuated through an LN_2 trap using an oil diffusion pump system.

During hi-pot testing, the high-voltage power supply is connected through a 2 MΩ resistor and the tube is filled with helium to a pressure of about 10 mTorr (this expedites conditioning due to the resulting ion bombardment). Activity is monitored by noting the high-voltage power supply current, x-ray emission and audible emissions.

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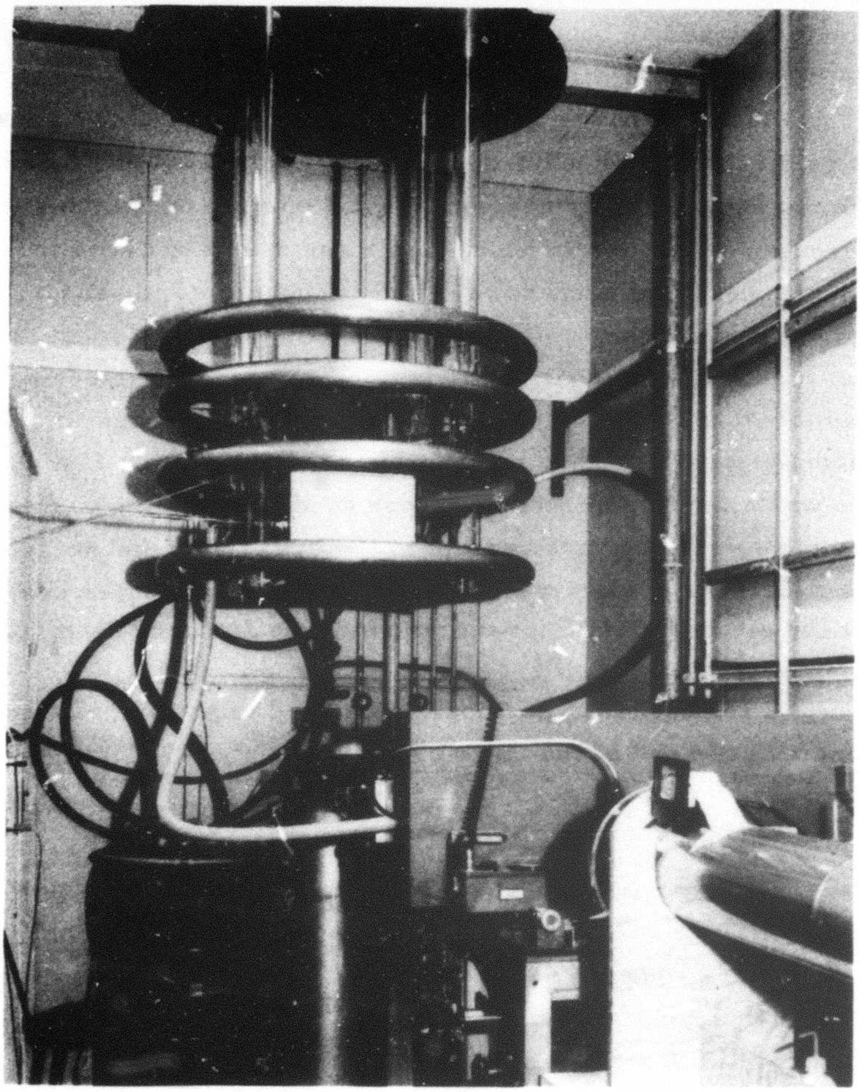

Fig. 7. Experimental assembly for evaluation of the 4 x 40 cm E-gun.

During E-gun operation the 2 MΩ resistor is replaced with an approximately 40 KΩ series resistor. Various low-voltage currents and voltages are monitored using meters located on the floating deck. Helium pressure is monitored by means of a DV-6M thermocouple gauge which is corrected using manufacturers data.

C. Experimental Results

The 4 x 40 cm plasma cathode E-gun, which is capable of both pulsed and cw operation, has been operated under cw conditions during the subject reporting period in order to provide design data for the 5 x 125 cm gun. Furthermore, all experiments to date have been performed with a solid collector plate in place of the foil window in order to avoid the complications of window heating.

High-voltage stand-off tests, which were performed without beam extraction, demonstrated the capability of the present design to operate at beam voltages up to 200 kV. As the voltage was initially increased some arcing and x-ray emission was observed which decreased in time. The 200 kV level was achieved after 1 to 2 hours of conditioning after tube assembly.

The E-gun characteristics with beam extraction are illustrated in Figs. 8 through 10. Figure 8 shows that the beam current I_B is proportional to the discharge current.* These data were obtained at a control grid potential of -23 V (the control potential is measured relative to the anode potential) for beam energies of 50 and 100 keV. The small current remaining when the discharge current is reduced to zero is due to electrons generated by the igniter. If the anode and control grids are connected to cathode potential this residual beam current is reduced to ~0.1 mA.

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*Although average cw beam current densities of up to 1 mA/cm^2 have been extracted with the low-voltage version of the present device, the tests described below were limited to 40 mA or 0.25 mA/cm^2 by high-voltage power supply constraints.

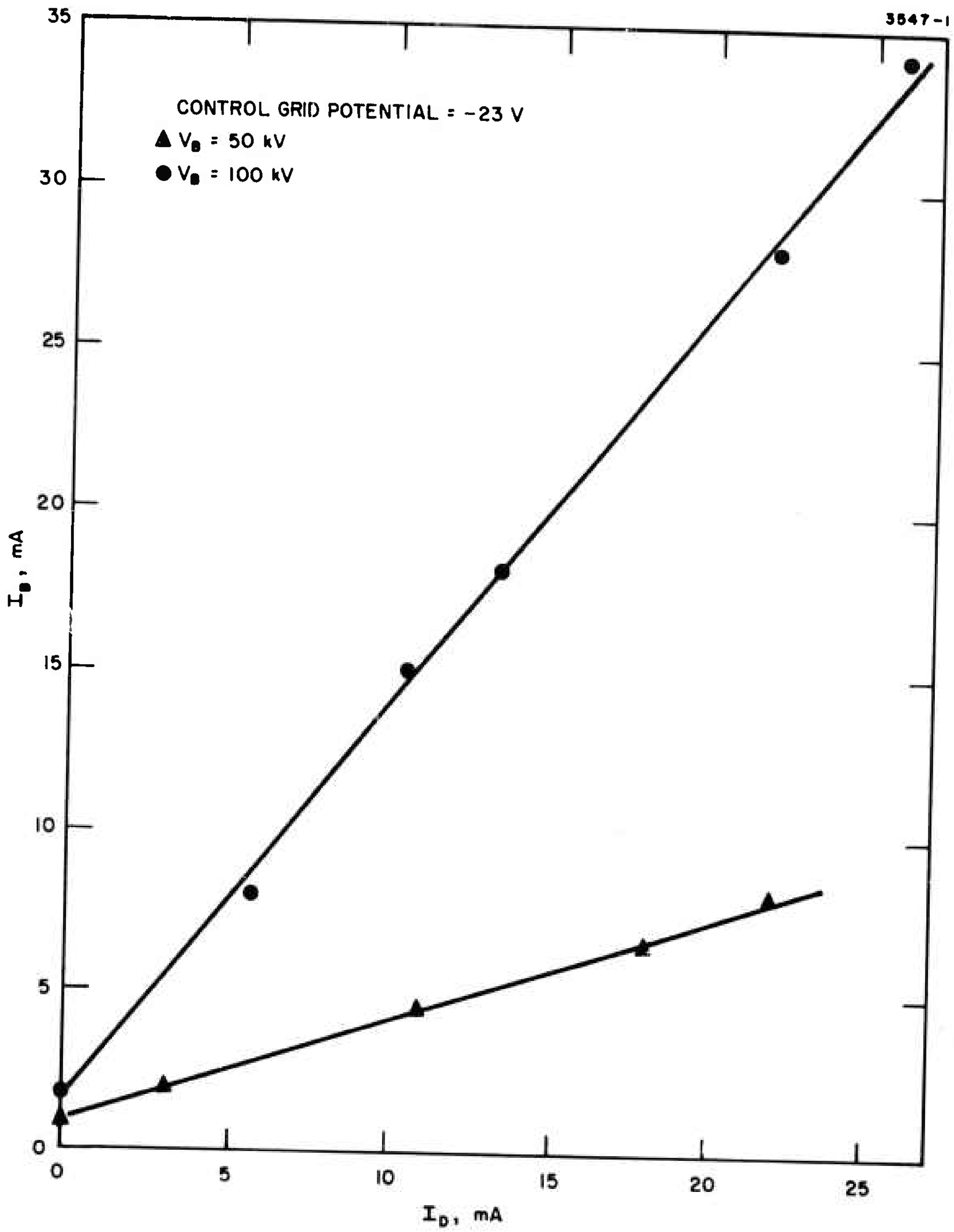

Fig. 8. Dependence of the electron beam current I_B on the discharge current I_D with beam voltage V_B as a parameter.

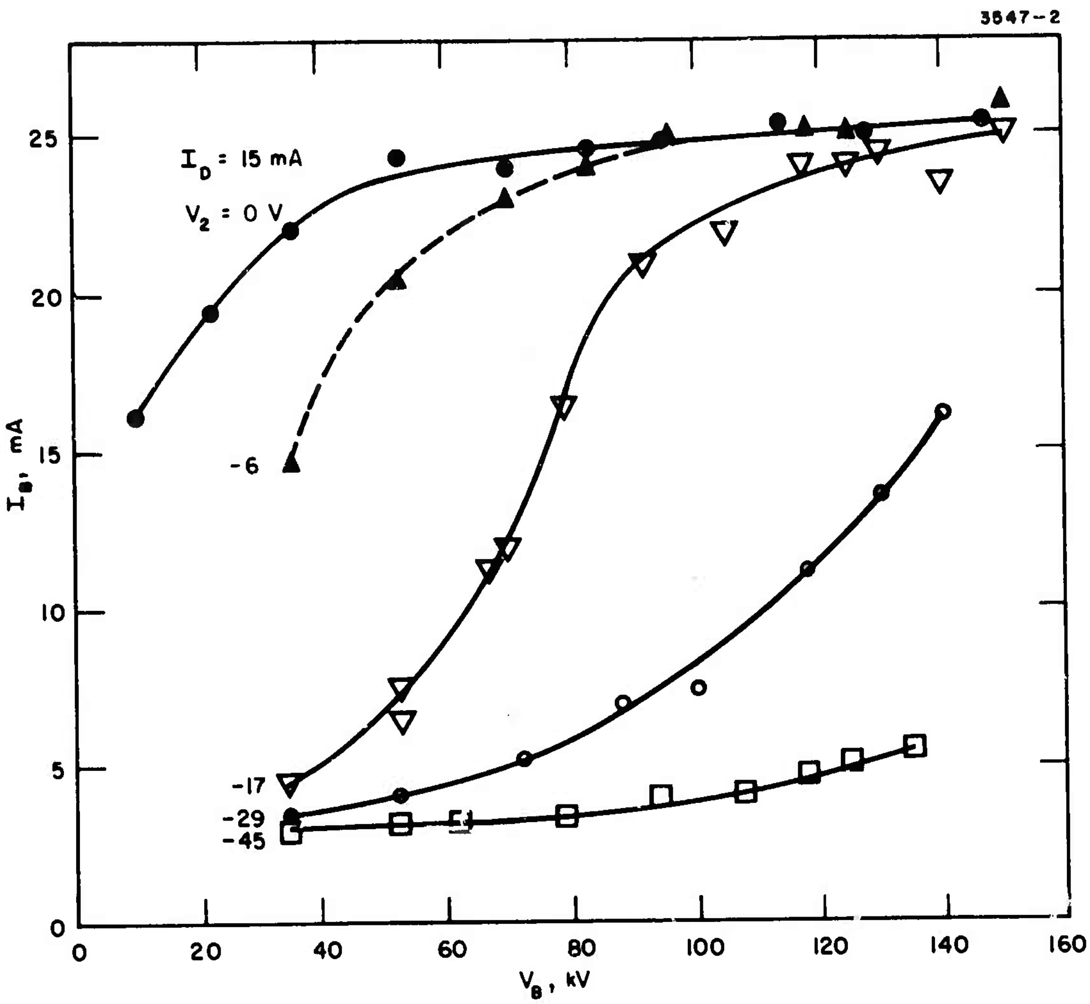

Fig. 9. Dependence of beam current I_B on beam voltage V_B with the control grid potential V_2 as a parameter.

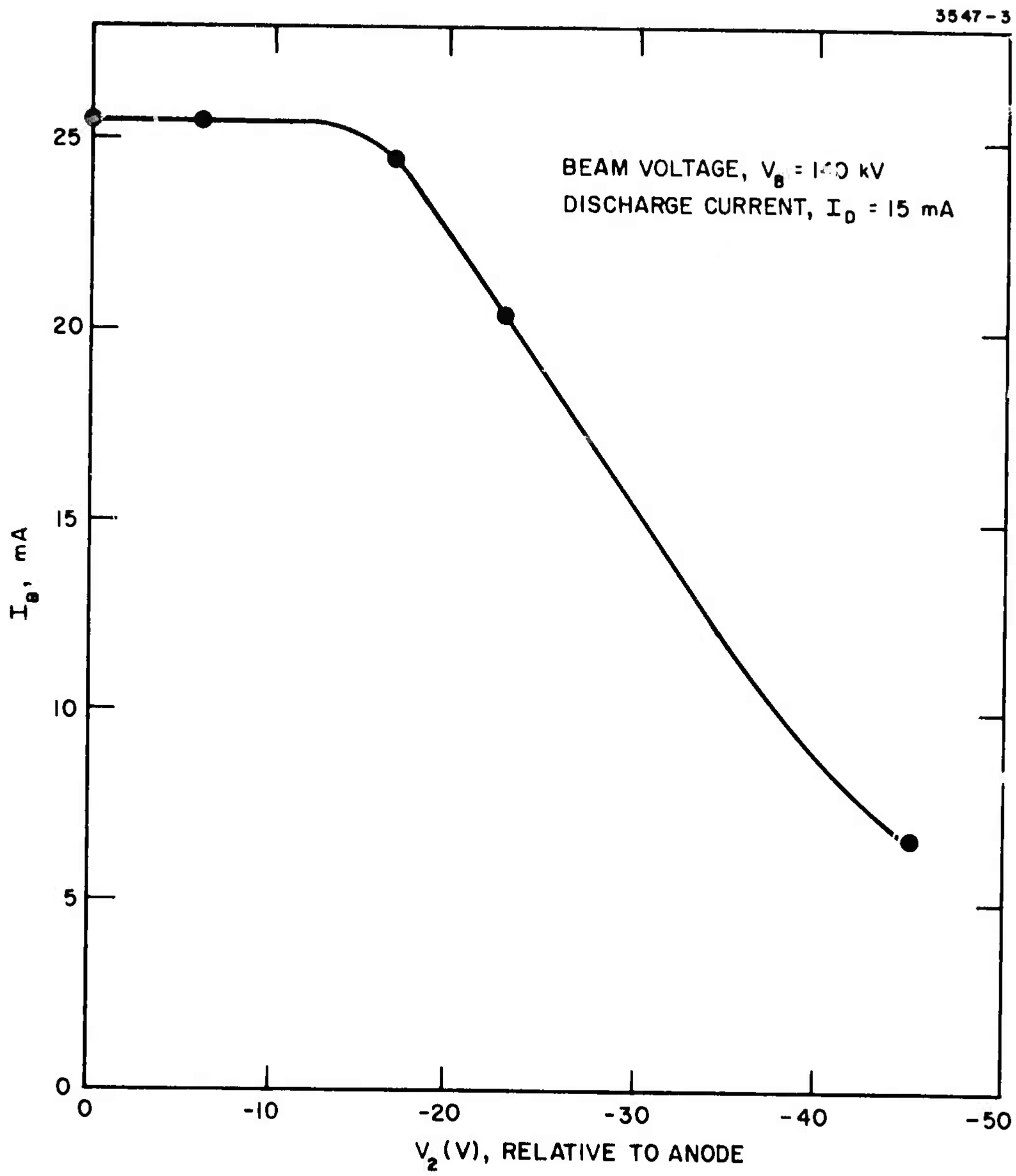

Fig. 10. Dependence of beam current on control gird potential.

Figure 9 shows the dependence of the beam current on beam voltage for various control grid potentials with the discharge current fixed. It is seen that the beam current saturates with beam voltage and that this saturation generally occurs at lower beam voltages as the control potential is made more positive. This data is partially replotted in Fig. 10, where I_B is given as a function of the control potential V_2 for a beam voltage of 140 kV. In this figure the saturation of I_B as V_2 becomes more positive is particularly evident.

The apparent potential of the control grid is given by

$$(V_2)_{\text{apparent}} = V_2 + \frac{V_B}{\mu}$$

where μ is the equivalent triode amplification factor.[2] This factor, which is obtained from the slope of V_B as a function of V_2 with I_B and I_D held constant, is approximately 4.3×10^3. Therefore, the departure from saturation in Fig. 10 occurs for an apparent control potential about 10 V positive with respect to the anode. The reason for this characteristic is not clear. The linear dependence of beam current on discharge current indicates that space charge limitations are not important. However, the positive value of the effective control potential should preclude electron retardation. This leaves the possibilities that the hollow-cathode plasma potential is being affected by the control potential and/or that a secondary plasma exists between the grids. Both of these situations are difficult to analyze on the basis of existing data.

The reason that I_B does not go to zero rapidly at the large negative control potentials, as shown in Fig. 10, is probably due to the electron energy distribution which contains both primary electrons with $E \sim 100$ eV and plasma electrons with $E \sim 1$ to 10 eV.

The saturated value of beam current indicated in Figs. 9 and 10 can be explained as follows. Electrons are only collected by "anode potential surfaces"; i.e., anode grid, control grid and window structure, since all other surfaces are negative with respect to plasma potential. Ions, however, are collected by both cathode and anode surfaces since both are negative with respect to the plasma. Under saturation conditions, when the apparent potential of the control grid is positive relative to the anode, the ions are reflected back to the anode grid. In addition, because the secondary electron yield due to ion impact on cathode surfaces is much less than unity, the total ion current is equal to the total electron current. In other words:

$$j_i A_T = j_e A_{AG}$$

where j_i and j_e are the collected ion and electron current densities respectively, and A_T and A_{AG} are the total and anode grid areas respectively. Since the control grid intercepts few electrons due to focusing of beam electrons through it, we can write:

$$I_B = j_e T A_{AG}$$

where T is the transmission of the anode grid. The current collected by the anode can be written as:

$$I_A = [j_e(1 - T) - j_i] A_{AG} .$$

The ratio I_B/I_A is then given at saturation by:

$$\frac{I_B}{I_A} = \frac{T}{(1 - T) - \left(\frac{j_i}{j_e}\right)} = \frac{T}{(1 - T) - \left(\frac{A_{AG}}{A_A}\right)} .$$

For our case $T \cong 0.53$ and $A_{AG}/A_A \cong 0.12$ so that $I_B/I_A \cong 1.5$. This agrees reasonably well with the experimentally indicated ratio of 1.66.

In these tests a beam current of 30 mA (0.19 mA/cm^2) was extracted from the discharge at up to 162 keV for 5 seconds. At this level small arcs (without high voltage power supply overload) occasionally occurred. At a beam energy of 150 keV such occurrances were rare and operation was quite reliable.

The current density distribution has been measured using two probe plates with similar results. One design had 33 collecting electrodes located behind 0.25-cm diameter apertures in a stainless steel plate. The other contained 21 1-cm diam collectors mounted on an aluminum plate. Measurements across the 4-cm beam width generally indicated a variation of ±10 to 15%, which is roughly consistent with previous results obtained with the low-voltage 4 x 40 cm device (±10%). Measurements along the long dimension indicate a variation of typically ±10 to 20%, a value which is greater than the value of ±5% measured with the low voltage device. The same distribution is obtained even when operating under conditions (beam voltage and current) similar to those employed with the low-voltage gun. Work is presently under way to determine the cause for this difference.

The electron beam stability was assessed through observation of the electron beam and discharge currents using Pearson current transformers and an oscilloscope. Generally, oscillations on the extracted beam are associated with ripple in the various power supplies. Since the beam current is proportional to the discharge current, ripple in the latter quantity influences the former. Therefore, it is desirable to use a constant current discharge power supply in order to minimize ripple on the electron beam.

Argon and air have been added to the helium working atmosphere with no noticeable effects on stability. They do, however, reduce the maximum operating pressure which is determined by Paschen breakdown. Measurements indicate that contamination with 30% argon or 20% air will result in a reduction in the maximum operating pressure by 50%. At the same time the minimum operating pressure which is determined, in part, by the ionization cross section of the gas mixture, is reduced. The net result, at least for these contaminants, is that rather large contamination levels are tolerable without seriously degrading the high-voltage operating characteristics.

The discharge itself acts as a pump for chemically active contaminants such as air and water. This is a result of sputtering produced by energetic ions striking the cathode surfaces. Measurements with the 4 x 40 cm gun indicate that the discharge pumps air at a rate of about 5×10^{-3} Torr-liter/s. This corresponds to a reduction in the partial pressure of air by 20 mTorr in 1 min. Thus, once the outgassing or leakage rate has been reduced below this level by conditioning (cycling between gun operation and evacuation) the discharge will remove any further contamination.

The influence of magnetic fields on the operation of the plasma cathode E-gun have been studied by observing the influence of dc magnetic fields on the beam current density distribution. Changes of 10% were observed for fields on the order of 1 G. This is apparently due to magnetic interactions with the hollow-cathode discharge. In contrast, perturbation of the trajectories of electrons emitted from the cathode of a thermionic E-gun become observable for fields of about 10 G. Thus, more care must be exercised with the plasma cathode E-gun to prevent magnetic interactions. However, simple calculations indicate that this can easily be achieved simply by employing reasonably compact laser circuitry.

IV. 5 x 125 cm E-GUN DEVELOPMENT

The objective of this portion of the plasma cathode development program is to design, construct and evaluate a full scale E-gun for application to a large laser system. The requirements chosen for this E-gun are:

● Beam Energy	150 to 175 keV
● Average Beam Current Density	0.1 to 0.5 mA/cm^2
● Minimum Operating Time	5 s
● Beam Dimensions at the Foil Window (nominal)	5 cm x 125 cm
● Beam Uniformity (long dimension)	±5%
● Half-angle of Beam Convergence at Window	$\sim 10^{\circ}$

The beam convergence is intended to help compensate for divergence at the edges of the beam due to scattering by the foil window. The convergence angle of $\sim 10^{\circ}$ is chosen as that which is achievable with a device having cross-sectional dimensions similar to those of the existing 4 x 40 cm plasma cathode E-gun with which most design data has been obtained.

A. Overall Design

Figures 11 and 12 show the design layout of the 5 x 125 cm plasma cathode E-gun. The basic design (the details of some aspects of the design development will be described later) is very similar to that of the 4 x 40 cm device with which the basic beam requirements have been approximately achieved. In the present design, however, the anode-control grid system is curved in order to provide the desired beam focusing.

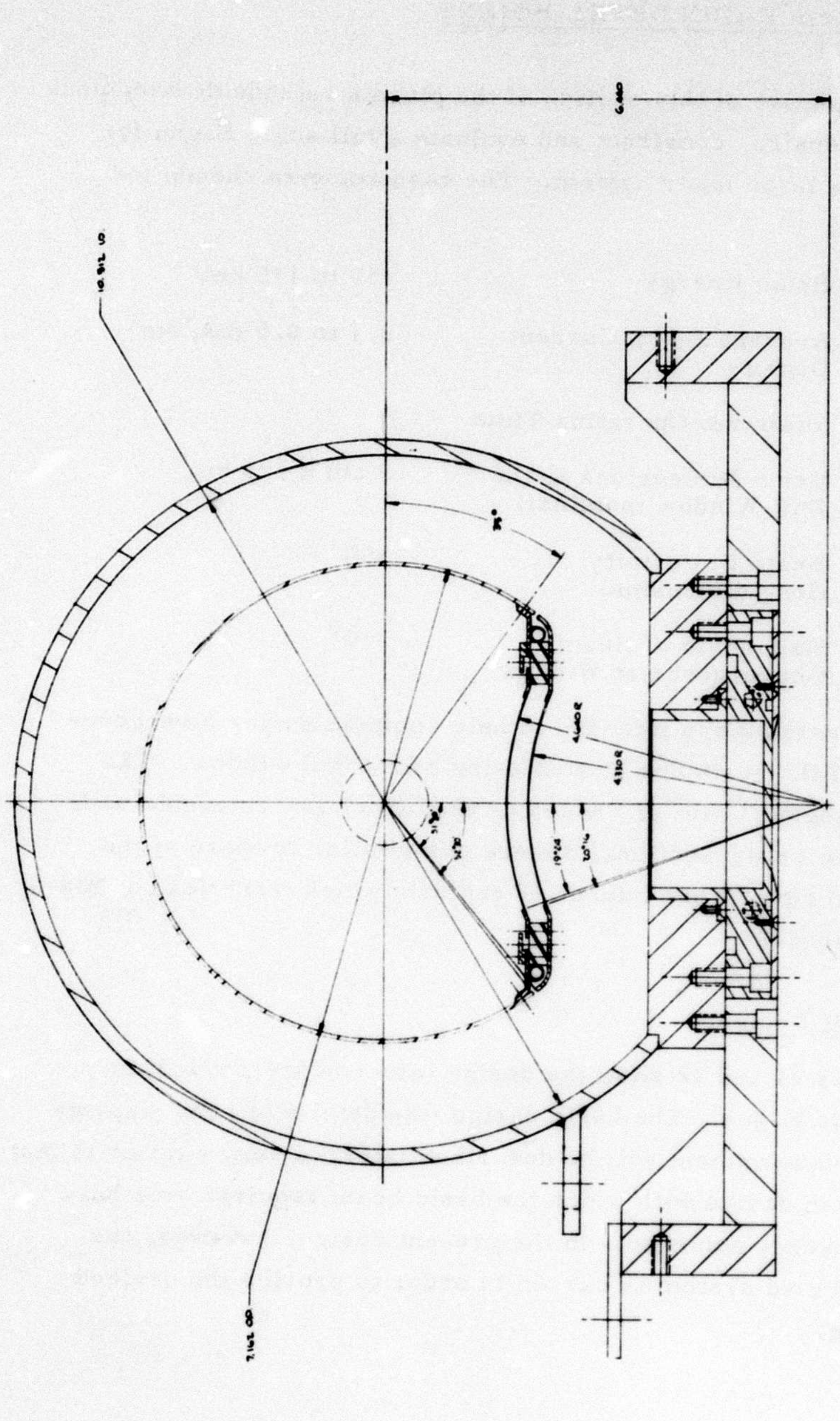

Fig. 11. Cross section of 5 x 125 cm plasma cathode E-gun.

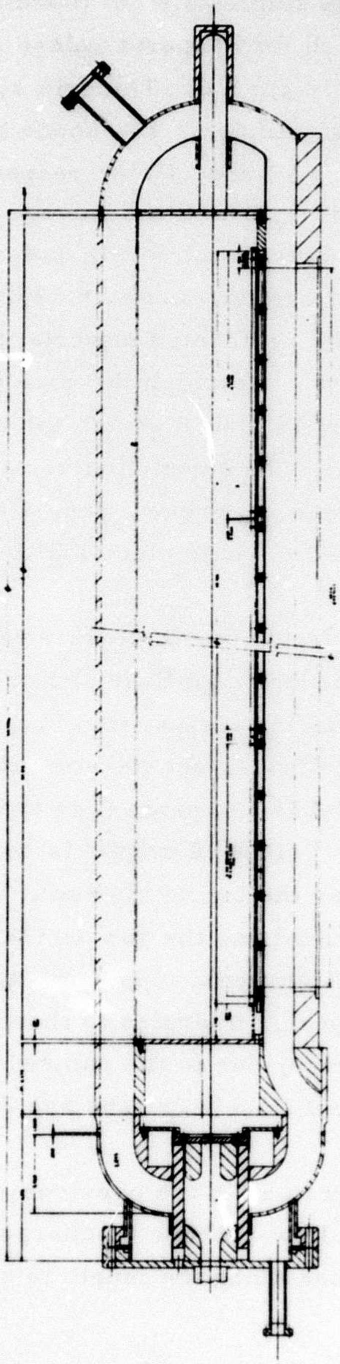

Fig. 12. Layout of 5 x 125 cm plasma cathode E-gun.

The cathode is formed by a 304 stainless steel (nonmagnetic 304, 315, or 321 stainless steel is used for all parts unless stated otherwise) cylinder of approximately 18 cm i.d. The grid system is supported by brackets attached to this cylinder. The anode and cathode grids have curvatures of approximately 12 and 11 cm, respectively, and are spaced 0.8 cm apart. The grids, which are formed from perforated stainless steel sheet stock 0.095-cm thick with 0.4-cm diameter holes and a transmission of 63%, are covered with 59% transparent stainless steel wire mesh. The perforated material provides mechanical support while the fine mesh, for which the wire spcaing of approximately 0.05 cm is less than the Debye sheath thickness, serves to define the plasma boundary. The supporting ceramic pieces are shielded, as in the 4 x 40 cm device, to prevent deposition of sputtered material. A metal tube used to route electrical leads is also included within this shielding.

The spacing between the inner and outer cylinders is maintained at close to 4 cm, thereby resulting in an E-gun outer diameter of 27 cm. In the grid region, this spacing varies from 3.6 cm to 4.5 cm due to the grid curvature. Following acceleration the electrons pass through a potential defining molybdenum mesh (78% transparent) and into a drift region 4.5-cm long. This drift region is necessitated in order to locate the foil window near the lasing medium. As shown in Fig. 11, a flange is provided which adapts the gun to the laser.

The high-voltage feedthrough, ceramic support post, and field shaping electrode structures, are similar in design to those of the 4 x 40 cm E-gun. In the present device, due to the somewhat larger gun diameter, the maximum electrical field strengths are 20 to 50% lower than in the 4 x 40 cm device.

On the basis of the results obtained in the previous scaling experiments with the 200-cm long hollow-cathode discharge,[1] the anode grid is divided into four sections along the length in order to aid in achieving the desired current density uniformity. Each section has a separate ballast resistor located within the vacuum envelope. The control grid is a unipotential surface; this is possible since the previously measured voltage differences between anodes is small ~0.1 V. Therefore, the variation in control voltage between anode sections, is not sufficient to cause significant perturbation of the beam current density. The grid system, as well as the foil and flange system, are designed without any major ribs which would shadow the beam.

The inner cylinder is removed by sliding it out through the end flange while it is supported by a teflon cradle inserted through the E-beam flange aperture.

Figure 13 shows the completed inner cylinder and vacuum envelope. The foil support structure and E-gun adapter flange are not present. Figure 14 shows the assembled gun mounted on its cart. The foil flange system is replaced with a probe assembly used to measure the local current density distribution. The LN_2 cold trap-helium supply system and the gun adapter flange are also shown.

B. Beam Focusing Considerations

In the design shown in Fig. 11, the beam width and convergence angle at the foil window are related to the overall cross-sectional dimensions of the discharge chamber through the prescribed ratio between anode and cathode areas. This ratio should be about six, based on the scaling studies described in the previous semiannual report.[1] Therefore, as the convergence angle and/or the extracted beam width are increased, the anode width and discharge chamber diameter must increase. Furthermore, as the convergence angle increases, the variation in distance between the curved control grid and the flat high-voltage acceleration electrode increases. This can clearly be compensated for by also curving the latter electrode, however, this complicates the design.

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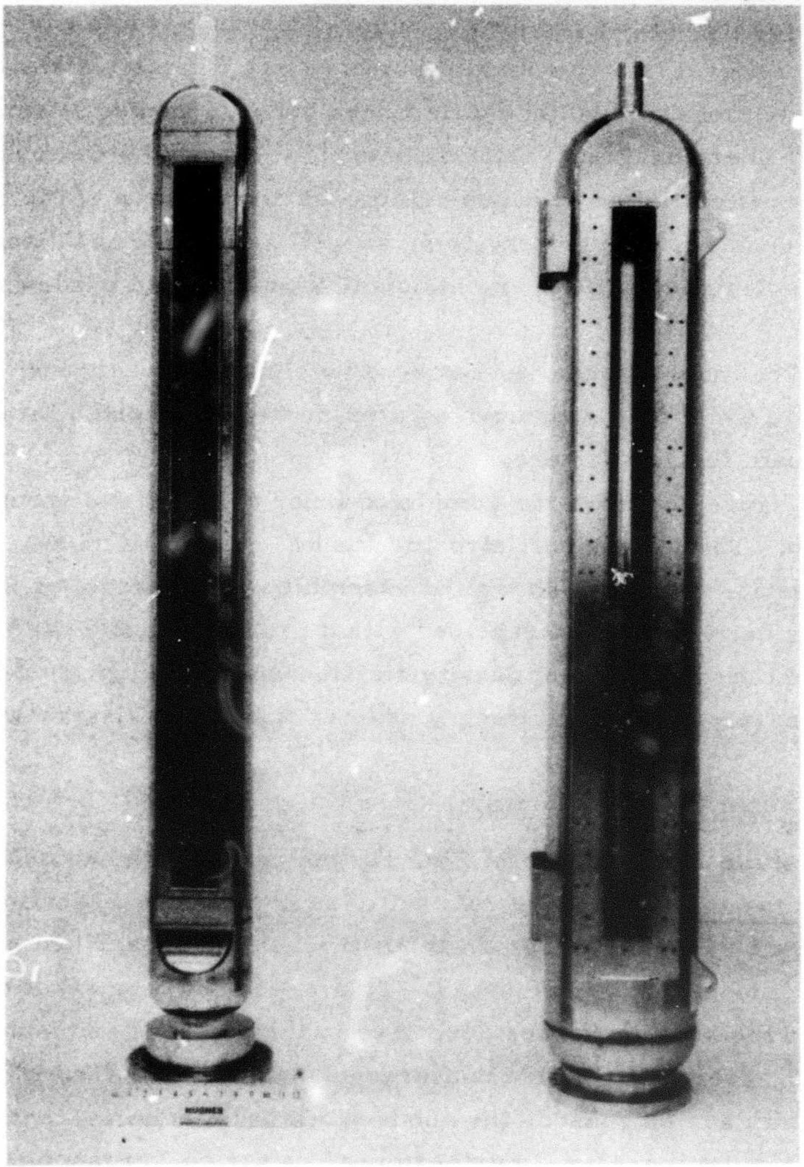

Fig. 13. Inner and outer cylinders of 5 x 125 cm E-gun.

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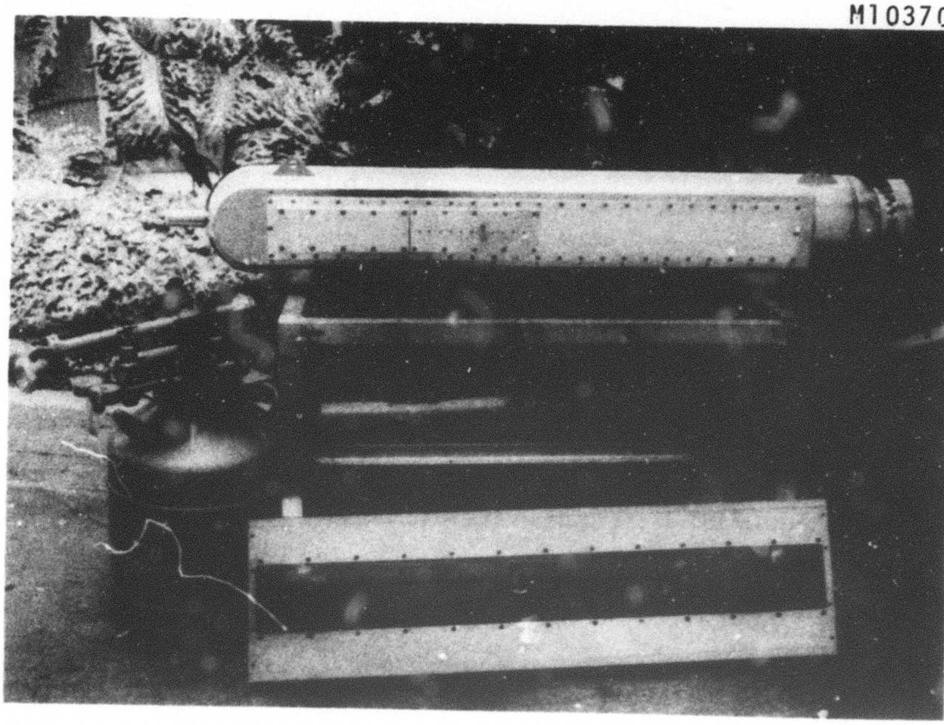

Fig. 14. Completed E-gun with adapter flange and LN_2 dewar-helium supply system.

Summarizing these arguments and the requirements outlined earlier leads to the following design criteria:

1. The cross-sectional design should not depart greatly from that of the 4 x 40 cm device and should be consistent with currently available material sizes.

2. Design simplicity should be maintained.

3. Convergence half-angle $\cong 10^{o}$.

4. Beam width $\cong$ 5 cm.

5. Anode-cathode area ratio $\cong$ 6.

6. Spacing between inner and outer cylinder $\cong$ 4 cm ±10%.

Evaluation of a number of designs with various grid curvatures has been performed with the aid of a digital computer program which provide the potential distribution within the acceleration region and the resultant electron trajectories. The design described earlier was chosen as that which most closely satisfied the above design criteria.

Figure 15 shows the dependence of the convergence angle at the foil window on the distance from the center of the window calculated for the present design. The peak of this curve is associated with the reversal in the curvature at the edges of the control grid which is necessary to minimize electric field concentrations. The beam edge is chosen as the peak of this curve which gives a beam width of 4.2 cm and a convergence angle of 9.4^{o}.

Figure 16 shows the effect of focusing on the transverse beam current density distribution assuming a uniform current density incident on the anode grid. It is seen that focusing leads to a 45% reduction of the beam current density at the beam edge.

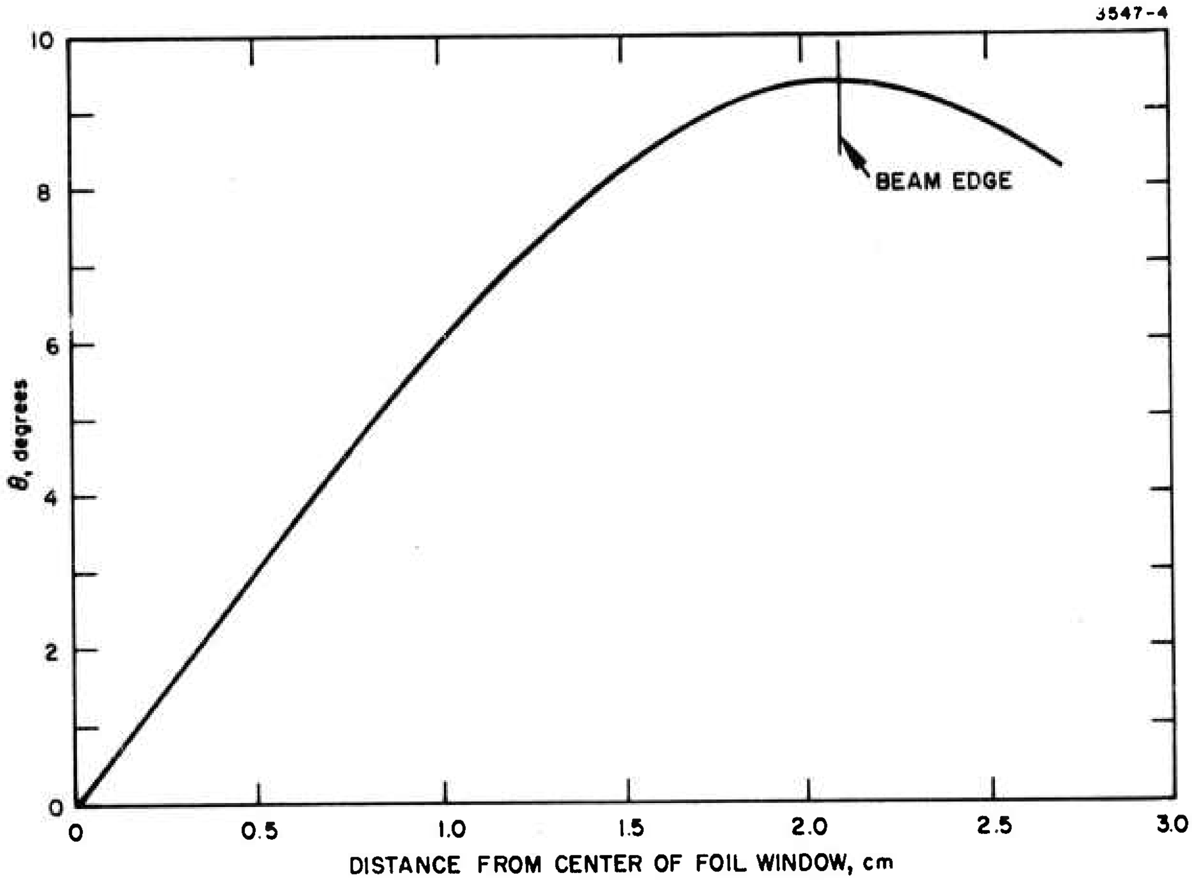

Fig. 15. Dependence of beam convergence angle at the foil window on the distance from the center of the beam.

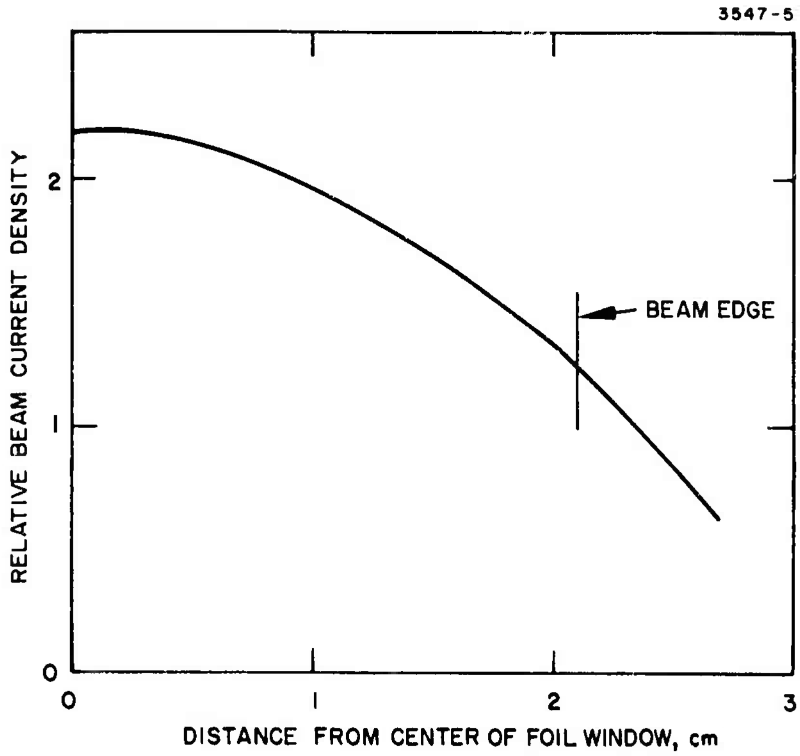

Fig. 16. Dependence of beam current density on the distance from the center of the foil window.

C. High-Voltage Anode Grid Design

The high-voltage anode grid as discussed previously, serves to define an equipotential surface on the positive side of the acceleration region. This component was formed by a molybdenum mesh in both the 4 x 40 cm and 5 x 125 cm E-guns. The design of this component is influenced by its: (1) thermal properties, (2) electrostatic focusing, (3) electrid field enhancement, (4) effect on Paschen breakdown, and (5) beam interception.

Heating of the high voltage anode grid is through direct bombardment by high energy electrons. Cooling can occur through radiation and conduction. Simple calculations show that the maximum temperature attained when radiation cooling alone is considered is given by:

$$T_{max}(^{o}K) = 770 \left[\frac{j_B V_B}{\epsilon (A_r / A_i)} \right]^{1/4}$$

where j_B is the beam current density after the foil window in amperes, V_B is the beam voltage in volts, ϵ is the emissivity of the grid, A_r is the area from which radiation takes place and A_i is the area which intercepts the E-beam. For a molybdenum grid with square or round bars intercepting 0.5 mA/cm^2 at 175 kV this temperature is 1900^{o}C while the melting point is 2610^{o}C.

The relationship for a bar grid, which is cooled by conduction to a cold flange, is given by:

$$T_{max}(^{o}C) = \frac{L^2}{4} \frac{j_B V_B}{k \ell} \ .$$

where L is the length of the bars, k is the thermal conductivity, and ℓ is the depth of the bars. For the same beam conditions as used above this gives a temperature which is close to the melting point for both molybdenum and copper bars with dimensions of 6 cm long and 0.2-cm deep. Thus, for these conditions radiation cooling would dominate.

Thermal conduction can be increased by increasing the depth of the bar grid, however, defocusing of the electron beam by the local potential distribution near the grid will lead to increased interception by the grid and a loss of grid transmission. It can easily be shown that the transmission of a bar grid is given approximately by

$$T = 1 - \frac{a}{A} - \frac{\ell}{2W},$$

where a is the bar width, A is the spacing between bar centers, ℓ is the depth and W is the width of the acceleration region. Referring to the previous example, if one increases ℓ to 0.4 cm then the third term in the above expression, which is due to defocusing, will result in a 5% loss in grid transmission.

An additional factor relating to the thermal properties is the thermal expansion. If a rigid bar grid is used, either the gun flange will be severely stressed or the bars will distort. It may be possible to design the bars so that they will distort in a controlled manner, but this is probably difficult. Alternatively, a fine molybdenum mesh such as has been employed above can be used. Such a mesh will lose heat by radiation and will operate at a temperature well below its melting point. Thermal expansion is easily allowed for through screen distortion (macroscopic distortion does not disturb the beam since its velocity is very high near the positive electrode). Furthermore, a fine mesh will not suffer unwanted transmission losses as a result of defocusing.

It is naturally important that the geometrical transmission of the high voltage anode grid be high. However, as the transmission increases, so does the electric field enhancement factor at the grid wires. If this factor becomes too large, vacuum breakdown will occur. The enhancement factor, which can be easily obtained starting from the development of Spangenberg,[2] is given by:

$$\delta = [1 - e^{-\pi(1-T)}]^{-1} ,$$

Table I illustrates how this factor depends on the grid transmission T. The average electric field strength in the acceleration region of the 5 x 125 cm E-gun at 175 kV is 40 kV/cm. Since it is generally desirable to maintain the field below about 70 kV/cm, the grid transmission should be between 70 and 80%. For this transmission, as determined with the 4 x 40 cm E-gun, there is negligible effect on the Paschen breakdown characteristics.

Thus, it is seen that 78% molybdenum mesh, as used with the 4 x 40 cm gun, is also readily suitable for the 5 x 125 cm E-gun.

TABLE I

Dependence of the Electric Field Enhancement Factor δ on Grid Transmission T

T(%)	δ
70	1.7
80	2.1
90	3.7
100	∞

T1426

V. CONCLUSIONS AND FUTURE PLANS

During the past six months, the plasma cathode electron gun concept has been extended through the development of two devices, a 4 x 40 cm and a 5 x 125 cm E-gun, which have designs well suited for use with laser systems. The 4 x 40 cm E-gun has been operated under cw conditions at 162 keV and a pre-foil current density of 0.19 mA/cm^2 (power supply limit) for 5 s. Results from this device have been incorporated into the 5 x 125 cm gun which has recently been completed. This device, which has an outer diameter of only 27 cm, will produce a beam which is focused with a convergence half-angle of ~10°. It will operate at a beam energy of 175 keV and a post-foil current density in the range 0.1 to 0.5 mA/cm^2 for longer than 5 s. Testing is presently under way to evaluate this device.

During the next six months of this program, work will be performed in the following areas:

- Further plasma cathode electron gun development with the 4 x 40 cm device.
- Evaluation of the 5 x 125 cm electron gun.
- Development of advanced plasma cathode devices.

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2. K. Spangenberg, Vacuum Tubes (McGraw-Hill, New York, 1948).